Chapter 11
Conservation Storage

11-1. General Considerations

a. Purposes. Water stored in the conservation pool can serve many purposes. The primary purposes for conservation storage are water supply, navigation, low-flow augmentation, fish and wildlife, and hydroelectric power. The water requirements for these purposes are discussed in this chapter along with water quality considerations. Methods for estimating the conservation storage, or yield, are presented in Chapter 12.

b. Operational policy. In general, the operational policy is to conserve available supplies and to release only when supplemental flow is needed to meet downstream requirements. Water stored in the conservation pool also provides benefits within the pool, such as lake recreation and fish and wildlife habitat.

c. Changing hydrology. When a reservoir is filled, the hydrology of the inundated area and its immediate surroundings is changed in a number of respects. The effects of inflows at the perimeter of the reservoir are translated rapidly to the reservoir outlet, thus, effectively speeding the flow of water through the reservoir. Also, large amounts of energy are stored and must be dissipated or utilized at the outlet. The reservoir loses water by evaporation, and this usually exceeds preproject evapotranspiration losses from the lake area. Siltation usually seals the reservoir bottom, but rising and falling water levels may alter the pattern of groundwater storage due to movement into and out of the surrounding reservoir banks. At high stages, water may seep from the reservoir through permeable soils into neighboring catchment areas and so be lost to the area of origin. Finally, sedimentation takes place in the reservoir and scour occurs downstream.

d. Storage allocation. The joint use of storage for more than one purpose creates problems of storage allocation for the various purposes. While retained in reservoir storage, water may provide benefits to recreation, fish, wildlife, hydropower, and aesthetics. Properly discharged from the reservoir, similar benefits are achieved downstream. Other benefits that can be derived from the reservoir are those covered in this chapter, including municipal and industrial water supply, agricultural water supply, navigation, and low-flow augmentation.

e. Supplemental storage capacity. In most areas, supplemental storage capacity is required for sediment deposition; otherwise, the yield capability of the reservoir may be seriously diminished during the project's economic life. Sediment storage is determined by estimating the average annual sediment yield per square mile of drainage area from observations in the region and multiplying by the drainage area and the economic life of the project. Trap efficiency of the reservoir is evaluated and the distribution of this estimated volume of sediment is determined, using methods described in EM 1110-2-4000 *Sedimentation Investigations of Rivers and Reservoirs*. Sediment surveys within the reservoir during actual operation will establish the reliability of these estimates. Storage allocation levels may then be revised if the sediment surveys show a significant difference between what was projected and what was measured. More complete descriptions of the techniques used to determine reservoir sedimentation are presented in EM 1110-2-4000.

f. Minimum pool. A minimum pool at the bottom of active conservation storage is usually established to identify the lower limit of normal reservoir drawdown. The inactive storage below the minimum pool level can be used for recreation, fish and wildlife, hydropower head, sediment deposition reserve, and other purposes. In rare instances, it might be used to relieve water supply emergencies.

g. Reservoir outlets. Reservoir outlets must be located low enough to withdraw water at desired rates with the reservoir stage at minimum pool. These outlets can discharge directly into an aqueduct or into the river. In the latter case, a diversion dam may be required downstream at the main canal intake.

h. Computing storage capacity. Because the primary function of reservoirs is to provide storage, their most important physical characteristic is storage capacity. Capacities of reservoirs on natural sites must usually be determined from topographic surveys. The storage capacity can be computed by planimetering the area enclosed within each elevation contour throughout the full range of elevations within the reservoir site. The increment of storage between any two elevation contours is usually computed by multiplying the average of the areas at the two elevations by the elevation difference. The summation of these increments below any elevation is the storage volume below that level. An alternative to the average-end-area method is the determination of the storage capacity by the conic method, which assumes that the volumes are more nearly represented by portions of a cone. This method is available in the HEC-1 *Flood Hydrograph Package* computer program and is described in the program user's manual. In the absence of adequate topographic maps, cross sections of the reservoir area are sometimes surveyed, and the capacity is computed from these vertical cross sections by using the formula for the volume of a prism.

11-2. Water Supply

a. Introduction. Water supply for any purpose is usually obtained from groundwater or from surface waters. Groundwater yields and the methods currently in use are covered in *Physical and Chemical Hydrogeology* (Domenico and Schwartz 1990). This discussion is limited to surface water supplies for low-flow regulation or for diversion to demand areas.

(1) In some cases, water supply from surface waters involves only the withdrawal of water as needed from a nearby stream. However, this source can be unreliable because streamflows can be highly variable, and the desired amount might not always be available. An essential requirement of most water supply projects is that the supply be available on a dependable basis. Reservoirs play a major role in fulfilling this requirement. Whatever the ultimate use of water, the main function of a reservoir is to stabilize the flow of water, either by regulating a varying supply in a natural stream or by satisfying a varying demand by the ultimate consumer. Usually, some overall loss of water occurs in this process.

(2) In determining the location of a proposed reservoir to satisfy water needs, a number of factors should be considered. The dam should be located so that adequate capacity can be obtained, social and environmental effects of the project will be satisfactory, sediment deposition in the reservoir and scour below the dam will be tolerable, the quality of water in the reservoir will be commensurate with the ultimate use, and the cost of storing and transporting the water to the desired location is acceptable. It is virtually impossible to locate a reservoir site having completely ideal characteristics, and many of these factors will be competitive. However, these factors can be used as general guidelines for evaluating prospective reservoir sites.

(3) In the planning and design of reservoirs for water supply, the basic hydrologic problem is to determine how much water a specified reservoir capacity will yield. Yield is the amount of water that can be supplied from the reservoir to a specified location and in a specified time pattern. Firm yield is usually defined as the maximum quantity of water that can be guaranteed with some specified degree of confidence during a specific critical period. The critical period is that period in a sequential record that requires the largest volume from storage to provide a specified yield. Chapter 12 describes procedures for yield determination.

b. Municipal and industrial water use. The water requirement of a modern city is so great that a community system capable of supplying a sufficient quantity of potable water is a necessity. The first step in the design of a waterworks system is a determination of the quantity of water that will be required, with provision for the estimated requirements of the future. Next, a reliable source of water must be located and, finally, a distribution system must be provided. Water at the source may not be potable, so water-purification facilities are ordinarily included as an integral part of the system. Water use varies from city to city, depending on the population, climatic conditions, industrialization, and other factors. In a given city, use varies from season to season and from hour to hour. Planning of a water supply system requires that the probable water use and its variations be estimated as accurately as possible.

(1) Municipal uses of water may be divided into various classes. Domestic use is water used in homes, apartment houses, etc., for drinking, bathing, lawn and garden sprinkling, and sanitary purposes. Commercial and industrial use is water used by commercial establishments and industries. Public use is water required in parks, civic buildings, schools, hospitals, churches, street washing, etc. Water that leaks from the system, unauthorized connections, and other unaccounted-for water is classified as loss and waste.

(2) The average daily use of water for municipal and industrial purposes is influenced by many factors. More water is used in warm, dry climates than in humid climates for bathing, lawn watering, air conditioning, etc. In extremely cold climates water may be wasted at faucets to prevent freezing of pipes. Water use is also influenced by the economic status of the users. The per capita use of water in slum areas is much less than that in high-cost residential districts. Manufacturing plants often require large amounts of water; however, some industries develop their own water supply and place little or no demand on a municipal system. The actual amount depends on the extent of the manufacturing and the type of industry. Zoning of the city affects the location of industries and may help in estimating future industrial demands.

(3) About 80 percent of industrial water may be used for cooling and need not be of high quality, but water used for process purposes must be of good quality. In some cases, industrial water must have a lower content of dissolved salts than can be permitted in drinking water.

The location of industry is often much influenced by the availability of water supply. If water costs are high, less water is used, and industries will often develop their own supply to obtain cheaper water. In this respect, the installation of water meters in some communities has reduced water use by as much as 40 percent. The size of the city being served is a factor affecting water use. Per capita use tends to be higher in large cities than in small towns. The difference results from greater industrial use, more parks, greater commercial use, and, perhaps, more loss and waste in the larger cities. All of these factors, plus estimated population projections, should be considered in designing a waterworks system.

(4) The use of water in a community varies almost continually. In midwinter the average daily use is usually about 20 percent lower than the daily average for the year, while in summer it may be 20 to 30 percent above the daily average for the year. Seasonal industries such as canneries may cause wide variation in water demand during the year. It has been observed that for most communities, the maximum daily use will be about 180 percent of the average daily use throughout the year. Within any day, large variations can be as low as 25 percent to as high as 200 percent of the average for portions of the day. The daily and hourly variations in water use are not usually considered in reservoir design, because most communities use distribution reservoirs (standpipes, etc.) to regulate for these variations.

c. Agricultural water use. The need for agricultural water supply is primarily for irrigation. Irrigation can be defined as the application of water to soil to supplement deficient rainfall in order to provide moisture for plant growth. In the United States, about 46 percent of all the water used is for irrigation. Irrigation is a consumptive use; that is, most of the water is transpired or evaporated and is essentially lost to further use.

(1) In planning an irrigation project a number of factors must be considered. The first step would be to establish the capability of the land to produce crops that provide adequate returns on the investment in irrigation works. This involves determining whether the land is arable (land which, when properly prepared for agriculture, will have a sufficient yield to justify its development) and irrigable.

(2) The amount of water required to raise a crop depends on the kind of crop and the climate. The plants that are the most important sources of food and fiber need relatively large amounts of water. The most important climatic characteristic governing water need is the length of the growing season. Other factors that affect water requirements are the quality of the water, the amount of land to be irrigated, and, of course, the cost of the water to the irrigator.

(3) In estimating the amount of storage that will be required in a reservoir for irrigation, the losses and waste that occur in the irrigation system must be considered. Losses and waste are usually divided into conveyance and irrigation losses and waste. Conveyance losses and waste are those that occur in the conveyance and distribution system prior to the application of water to crops. These are dependent on the design and construction of the system and also on how the system is operated and maintained. Irrigation losses and waste are those that occur due to the slope of the irrigated land, the preparation of the land, soil condition, the method of irrigation, and the practices of the irrigator.

(4) Usually, most of the irrigation losses and waste, as well as a portion of the water applied to the irrigated lands, return to the stream. If there are requirements for flow downstream of the reservoir, these return flows can be important in determining the amount of water that must be released to meet such requirements.

(5) In most areas, the need for irrigation water is seasonal and depends on the growing season, the number of crops per year, and the amount of precipitation. For these reasons the variation of the demand is often high, ranging from no water for some months up to 20 to 30 percent of the annual total for other months. This variation can have a very large effect on the amount of storage required and the time of year when it is available.

11-3. Navigation and Low-Flow Augmentation

a. Objective. In designing a reservoir to supply water for navigation and low-flow augmentation, the objective is significantly different from objectives for the other purposes that have been discussed previously in this chapter. The objective is to supplement flows at one or more points downstream from the reservoir. For navigation, these flows aid in maintaining the necessary depth of water and alleviate silting problems in the navigable channel. Low-flow augmentation serves a number of purposes including recreation, fish and wildlife, ice control, pollution abatement, and run-of-river power projects. Under certain conditions, low-flow augmentation provides water for the other purposes discussed in this chapter. For instance, if the intake for a municipal and industrial water supply is at some point downstream of the reservoir, the objective may be to supplement low flows at that point.

b. Criteria for navigability. There are no absolute criteria for navigability and, in the final analysis, economic criteria control. The physical factors that affect the cost of waterborne transport are depth of channel, width and alignment of channel, locking time, current velocity, and terminal facilities. Commercial inland water transport is, for the most part, accomplished by barge tows consisting of 1 to 10 barges pushed by a shallow-draft tug. The cost of a trip between any two terminals is the sum of the fuel costs and wages, fixed charges, and other operating expenses depending on the time of transit. Reservoirs aid in reducing these costs by providing the proper depth of water in the navigation channel, or by providing a slack-water pool in lock and dam projects. Storage reservoirs can rarely be justified economically for navigation purposes alone and are usually planned as multipurpose projects. Improving navigation by using reservoirs is possible when flood flows can be stored for release during low-flow seasons.

c. Supplying deficiencies without waste. The ideal reservoir operation for navigation or low-flow augmentation would provide releases so timed as to supply the deficiencies in natural flow without waste. This is possible only if the reservoir is at the head of a relatively short control reach. As the distance from the reservoir to the reach is increased, releases must be increased to allow for uncertainties in estimating intermediate runoff and for evaporation and seepage enroute to the reach to be served. Moreover, the releases must be made sufficiently far in advance of the need to allow for travel time to the reach, and in sufficient quantity so that after reduction by channel storage, the delivered flows are adequate. The water requirement for these releases is considerably greater than the difference between actual and required flows.

d. Climate. Climate can also affect reservoir operation for low-flow regulation. Depending on the purpose to be served, the releases may be required only at certain times of the year or may vary from month to month. For pollution abatement, the important factors are the quality of the water to be supplemented, the quality of the water in the reservoir, and the quality standard to be attained. Also, the level of the intakes from which releases will be made can be a very sufficient factor in pollution abatement, since the quality can vary from one level to another in the reservoir. Long-term variations can occur due to increased contamination downstream of a reservoir. This should be considered in determining the required storage in the reservoir.

11-4. Fish and Wildlife

a. Added authorized purposes. As shown in Figure 2-1, fish and wildlife and subsequent environmental purposes have been added as authorized purposes since 1960. Because many of the reservoirs were built prior to that time, their authorized purposes and regulation plans may not adequately reflect the more recent environmental objectives. Therefore, there is an increasing demand and need for the evaluation of environmental impacts for these projects.

b. Water level fluctuations. The seasonal fluctuation that occurs at many flood control reservoirs and the daily fluctuations that occur with hydropower operation often result in the elimination of shoreline vegetation and subsequent shoreline erosion, water quality degradation, and loss of habitat for fish and wildlife. Adverse impacts of water level fluctuations also include loss of shoreline shelter and physical disruption of spawning and nests.

c. Water level management. Water-level management in fluctuating warm-water and cool-water reservoirs generally involves raising water levels during the spring to enhance spawning and the survival of young predators. Pool levels are lowered during the summer to permit regrowth of vegetation in the fluctuation zone. Fluctuations may be timed to benefit one or more target species; therefore, several variations in operation may be desirable. In the central United States, managers frequently recommend small increases in pool levels during the autumn for waterfowl management.

d. Fishery management. Guidelines to meet downstream fishery management potentials are developed based on project water quality characteristics and water control capabilities. To do so, an understanding of the reservoir water quality regimes is critical for developing the water control criteria to meet the objectives. For example, temperature is often one of the major constraints of fishery management in the downstream reach, and water control managers must understand the temperature regime in the pool and downstream temperature requirements, as well as the capability of the project to achieve the balance required between the inflows and the releases. Releasing cold water downstream where fishery management objectives require warm water will be detrimental to the downstream fishery. Conversely, releasing warm water creates difficulty in maintaining a cold-water fishery downstream.

e. Water temperature management. Water control activities can also impact water temperatures within the pool by changing the volume of water available for a particular layer. In some instances, cold-water reserves may be necessary to maintain a downstream temperature objective in the late summer months; therefore, the availability of cold water must be maintained to meet this objective. For some projects, particularly in the southern United States, water control objectives include the maintenance of warm-water fisheries in the tailwaters. In other instances, fishery management objectives may include the maintenance of a two-story fishery in a reservoir, with a warm-water fishery in the surface water, and a cold-water fishery in the bottom waters. Such an objective challenges water control managers to regulate the project to maintain the desired temperature stratification while maintaining sufficient dissolved oxygen in the bottom waters for the cold-water fishery. Regulation to meet this objective requires an understanding of operational affects on seasonal patterns of thermal stratification, and the ability to anticipate thermal characteristics.

f. Minimum releases. Minimum instantaneous flows can be beneficial for maintaining gravel beds downstream for species that require this habitat. However, dramatic changes in release volumes, such as those that result from flood-control regulation, as well as hydropower, can be detrimental to downstream fisheries. Peaking hydropower operations can result in releases from near zero to very high magnitudes during operations at full capacity. Maintaining minimum releases and incorporating reregulation structures are two of the options available to mitigate this problem.

g. Fishing versus peak power. In some instances, tailwater fishing is at a maximum during summer weekends and holidays, and this is a time when power generation may be at a minimum and release near zero. Maintaining minimum releases during weekend daylight hours may improve recreational fishing, but may reduce the capability to meet peak power loads during the week because of lower water level (head) in the reservoir. In these instances, water control managers will be challenged to regulate the project with consideration of these two objectives.

h. Anadromas fish. Regulation for anadromous fish is particularly important during certain periods of the year. Generally, upstream migration of adult anadromous fish begins in the spring of each year and continues through early fall, and downstream migration of juvenile fish occurs predominantly during the spring and summer months. The reduced water velocities through reservoirs, in comparison with preproject conditions, may greatly lengthen the travel time for juvenile fish downstream through the impounded reach. In addition, storage for hydropower reduces the quantity of spill, and as a result, juvenile fish must pass through the turbines. The delay in travel time subjects the juvenile fish to greater exposure to birds and predator fish, and passage through the powerhouse turbines increases mortality. To improve juvenile survival, storage has been made available at some projects to augment river flows, and flows are diverted away from the turbine intakes and through tailraces where the fish are collected for transportation or released back into the river. Barges or tank trucks can be used to transport juveniles from the collector dams to release sites below the projects. Other Corps projects have been modified so the ice and trash spillways can be operated to provide juvenile fish passage.

i. Wildlife habitat. Project regulation can influence wildlife habitat and management principally through water level fluctuations. The beneficial aspects of periodic drawdowns on wildlife habitat are well documented in wildlife literature. Drawdowns as a wildlife management technique can, as examples, allow the natural and artificial revegetation of shallows for waterfowl, permit the installation and maintenance of artificial nesting structures, allow the control of vegetation species composition, and ensure mast tree survival in greentree reservoirs. Wildlife benefits of periodic flooding include inhibiting the growth of undesirable and perennial plants, creating access and foraging opportunities for waterfowl in areas such as greentree reservoirs, and ensuring certain water levels in stands of vegetation to encourage waterfowl nesting and reproduction.

11-5. Hydroelectric Power

a. General. The feasibility of hydroelectric development is dependent upon the need for electric power, the availability of a transmission system to take the power from the point of generation to the points of demand, and the availability of water from streamflow and storage to produce power in accordance with the capacity and energy demands in the power market area. Also, the project's power operations must be coordinated with the operations for other project purposes to ensure that all purposes are properly served. Each of these factors must be investigated to ensure that the project is both feasible and desirable and to minimize the possibility that unforeseen conflicts will develop between power and other water uses during the project life.

(1) The ability of a project to supply power is measured in terms of two parameters: **capacity** and **energy**. **Capacity**, commonly measured in kilowatts (kw), is the maximum amount of power that a generating plant can deliver. **Energy**, measured in kilowatt-hours (kwh), is the

amount of actual work done. Both parameters are important, and the operation of a hydroelectric project is sensitive to changes in the demand for either capacity or energy.

(2) Experience has indicated that it is very unlikely that power demands will remain unchanged during the project life. Furthermore, the relative priority of various other water uses can change during the project life, and there are often legal, institutional, social, or environmental factors that might affect the future use of water at a particular project. Consequently, the feasibility studies for a proposed project must not be limited to conditions that are only representative of the current time or the relatively near future. Instead, the studies must include considerations of future conditions that might create irreconcilable conflicts unless appropriate remedial measures are provided for during project formulation.

(3) This section presents general concepts for the hydrologic analyses associated with the planning, design, and operation of hydroelectric projects and systems. More detailed information is provided in EM 1110-2-1701. Other investigations that influence or affect the hydrologic studies will be discussed to the extent that their outcome must be understood by the hydrologic engineer.

b. Types of hydroelectric load. Power developments, for purposes of this discussion, can be classified with respect to the type of load served or the type of site development proposed. The two categories related to the type of load served are baseload and peaking plants.

(1) Base load. Baseload plants are projects that generate hydroelectric power to meet the baseload demand. The baseload demand is the demand that exists 100 percent of the time. The baseload can readily be seen in Figure 11-1 as the horizontal dashed line on a typical annual load duration curve. This curve displays the percent of time during a given year that a given capacity demand is equaled or exceeded. The area under this curve represents the total energy required to meet the load during the year. Usually, the baseload demand is met by thermal generating facilities. However, in cases where there is a relatively abundant supply of water that is available with a high degree of reliability and where fuel is relatively scarce, hydroelectric projects may be developed to meet the baseload demands. These projects would then operate at or near full capacity 24 hr per day for long periods of time. This type of development is not feasible where there is a large seasonal variation in streamflow unless the baseflow is relatively high or unless there is a provision for a large volume of power storage in the project.

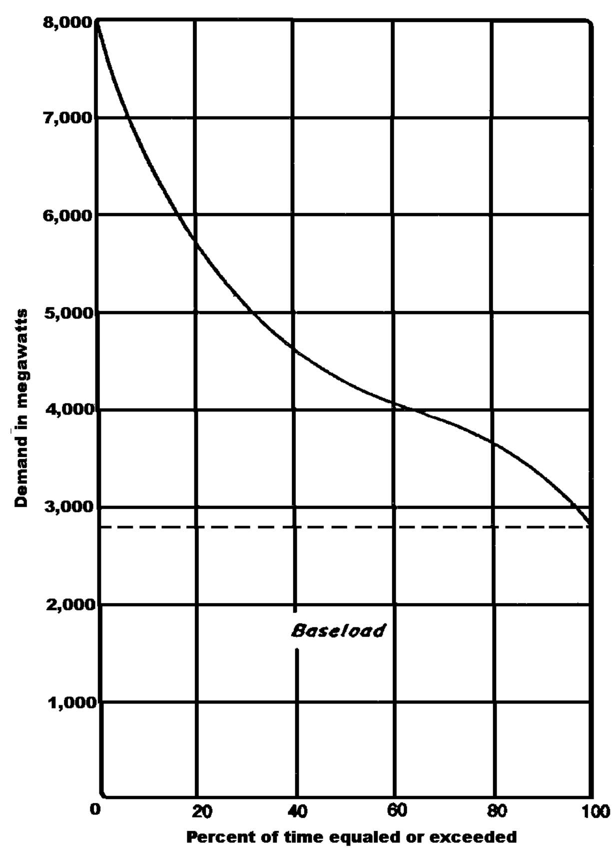

Figure 11-1. Typical annual load duration curve

(2) Peaking load. Peaking plants are projects that generate hydroelectric power to supplement baseload generation during periods of peak power demands. The peak power demands are the loads that exist primarily during the daylight hours. The time of occurrence and magnitude of peak power demands are shown on a load curve in Figure 11-2. This curve shows the time variation in power demands for a typical week. Depending upon the quantity of water available and the demand, a peaking plant may generate from as much as 18 hr a day to as little as no generation at all, but it is usually 8 hr a day or less. Peaking plants must supply sufficient capacity to satisfy the peak capacity demands of a system and sufficient energy to make the capacity usable on the load. This means that energy or water should be sufficient to supply peaking support for as long and as often as the capacity is needed. In general, a peaking hydroelectric plant is desirable in a system that has thermal generation facilities to meet the baseload demands. The hydroelectric generating facilities are particularly adaptable to the peaking operation because

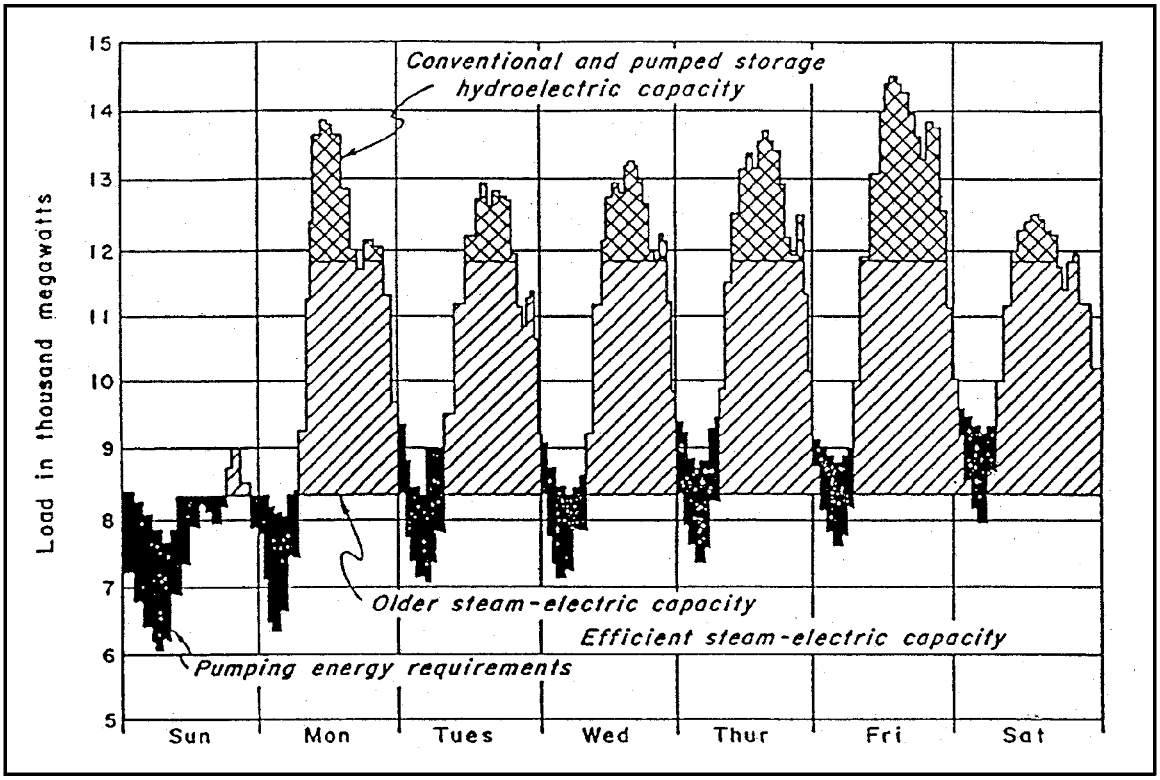

Figure 11-2. Weekly load curve for a large electric system

their loading can be changed rapidly. Also, the factors that make seasonal variations in streamflow a major problem in baseload operation are usually quite easily overcome in a peaking plant if some storage can be provided.

c. Project types. There are three major classifications of hydroelectric projects: storage, run-of-river, and pumped storage. There are also combinations of projects that might be considered as separate classifications, but for purposes of discussing hydrologic analysis it is necessary to define only these three types.

(1) Storage projects. Storage plants are projects that usually have heads in the medium to high range (> 25 m) and have provisions for storing relatively large volumes of water during periods of high streamflow in order to provide water for power generation during periods of deficient streamflow. Considerable storage capacity may be required because the period of deficient flow is quite frequently more than a year long and, in some instances, may be several years long. Because use of the stored water entails drawdown of the power storage, it is desirable that other water uses associated with the development of a storage plant permit frequent and severe drawdowns during dry periods. Peaking operation, which is quite frequently associated with storage projects requires large and sometimes rapid fluctuations in releases of water through the generating units. It is often necessary to provide facilities to re-regulate the power releases if fluctuations of water levels below the project are not tolerable. Because storage projects are conducive to multipurpose use and because the power output from a storage plant is a function of the guaranteed output during a multi-year dry period, it is usually necessary to make detailed routing studies to determine the storage requirements, installed capacity, firm energy, and an operating plan.

(2) Run-of-river projects. Run-of-river plants have little or no power storage and, therefore, must generate power from streamflow as it occurs. The projects generally have productive heads in the low to medium range (5-30 m) and are quite frequently associated with navigational developments or other multipurpose developments with limitations on reservoir drawdowns. Because of the absence or near-absence of storage in run-of-river projects, there is usually very little operational flexibility in these projects, and it is necessary that all water uses be compatible. The existence of one or more storage projects in the upstream portion of a river basin may make a run-of-river project in the lower portion of the basin feasible where it would not otherwise be feasible. In this situation, the storage projects provide a regulated outflow

that is predictable and usable, while the natural streamflow might be neither.

(a) Run-of-river projects may have provisions for a small amount of storage, often called pondage. This pondage detains the streamflow during off-peak periods in daily or weekly cycles for use in generating power during peak demand periods. If the cycle of peaking operation is a single day, the pondage requirements are based on the flow volume needed to sustain generation at or near installed capacity for 12 hr. If more storage capacity is available and large fluctuations in the reservoir surface are permissible, a weekly cycle of peaking operation may be considered. Because industrial and commercial consumption of power is significantly lower on weekends than on week days, an “off-peak” period is created from Friday evening until Monday morning. If generation from the hydroelectric peaking plants is not required during this period, water can be stored in the pondage for use during the 5-day peak-load period.

(b) Because of the relatively low heads associated with run-of-river projects, the tailwater fluctuations are usually quite important, particularly in peaking operations. Also, flood flows may curtail power generation due to high tailwater. While flow-duration analysis can be used to estimate average annual energy production, sequential analysis may be required for more detailed analysis of extreme conditions.

(3) Pumped-storage projects. Pumped-storage plants are projects that depend on pumped water as a partial or total source of water for generating electric energy. This type of project derives its usefulness from the fact that the demand for power is generally low at night and on weekends; therefore, pumping energy at a very low cost will be available from idle thermal generating facilities or run-of-river projects. If there is a need for peaking capacity and if the value of peaking power generation sufficiently exceeds the cost of pumping energy (at least a ratio of 1.5 to 1.0 because roughly 3 kwh of pumping energy are necessary to deliver enough water to provide 2 kwh of energy generation), pumped storage might be feasible. There are three types of pumped-storage development: diversion, off-channel, and in-channel, which are detailed in Chapter 7 of EM 1110-2-1701.

(a) In general, pumped storage projects consist of a high-level forebay where pumped water is stored until it is needed for generation and a low-level afterbay where the power releases are regulated, if necessary, and from which the water is pumped. The pumping and generating are done by generating units composed of reversible pump turbines and generator motors located along a tunnel or penstock connecting the forebay and afterbay. The water is pumped from the afterbay to the forebay when the normal power demand is low and least expensive and released from the forebay to the afterbay to generate power when the demand is high and most costly. The feasibility of pumped-storage developments is dependent upon the need for relatively large amounts of peaking capacity, the availability of pumping energy at a guaranteed favorable cost, and a load with an off-peak period long enough to permit the required amount of pumping.

(b) A unique feature of pumped-storage systems is that very little water is required for their operation. Once the headwater and tailwater pools have been filled, only enough water is needed to take care of evaporation and seepage. For heads up to 300 m, reversible pump turbines have been devised to operate at relatively high efficiency as either a pump or turbine. The same electrical unit serves as a generator and motor by reversing poles. Such a machine may reduce the cost of a pumped-storage project by eliminating the extra pumping equipment and pump house. The reversible pump turbine is a compromise in design between a Francis turbine and a centrifugal pump. Its function is reversed by changing the direction of rotation.

d. Need for hydroelectric power. The need for power is established by a power market study or survey. The feasibility of a particular hydroelectric project or system is determined by considering the needs as established by the survey, availability of transmission facilities, and the economics of the proposed project or projects. Although forecasts of potential power requirements within a region to be served by a project are not hydrologic determinations, they are essential to the development of plans for power facilities and to the determination of project feasibility and justification. The power market survey is a means of evaluating the present and potential market for electrical power in a region.

(1) The survey must provide a realistic estimate of the power requirements to be met by the project and must show the anticipated rate of load growth from initial operation of the project to the end of its economic life. The survey also provides information regarding the characteristics of the anticipated demands for power. These characteristics, which must be considered in hydrologic evaluations of hydroelectric potential, include the seasonal variation of energy requirements (preferably on a monthly basis), the seasonal variation of capacity requirements (also preferably on a monthly basis), and the range of usable plant factors for hydroelectric projects under both adverse and average or normal flow conditions.

(2) The results of a power market survey might be furnished to the hydrologic engineer in the form of load duration or load curves (Figures 11-1 and 11-2) showing the projected load growth, the portion of the load that can be supplied by existing generating facilities, and the portion that must be supplied by future additions to the generating system. From these curves, the characteristics of planned hydroelectric generating facilities can be determined. Because these data are developed from the needs alone without consideration of the potential for supplying these needs, the next step is to study the potential for hydroelectric development, given the constraints established in the study of needs.

e. Estimation of hydroelectric power potential. Traditionally, hydroelectric power potential has been determined on the basis of the critical hydro-period as indicated by the historical record. The critical hydro-period is defined as the period when the limitations of hydroelectric power supply due to hydrologic conditions are most critical with respect to power demands. Thus, the critical period is a function of the power demand, the streamflow, and the available storage. In preliminary project planning, the estimates of power potential are often based on a number of simplifying assumptions because of the lack of specific information for use in more detailed analyses. Although these estimates and the assumptions upon which they are based are satisfactory for preliminary investigations, they are not suitable for every level of engineering work. Many factors affecting the design and operation of a project are ignored in these computations. Therefore, detailed sequential analyses of at least the critical hydro-period should be initiated as early as possible, usually when detailed hydrologic data and some approximate physical data concerning the proposed project become available. Because of the availability of computer programs for accomplishing these sequential routings, they can be done rapidly and at a relatively low cost.

(1) The manner in which the streamflow at a given site is used to generate power depends upon the storage available at the site, the hydraulic and electrical capacities of the plant, streamflow requirements downstream from the plant, and characteristics of the load to be served. In theory, the hydroelectric power potential at a particular site, based on repetition of historical runoff, can be estimated by identifying the critical hydro-period and obtaining estimates of the average head and average streamflow during this critical period. The data can then be used in the equation below to calculate the power available from the project:

$$kW = \frac{1}{11.81} QHe \tag{11-1}$$

In order to convert a project's power output to energy, Equation 11-1 must be integrated over time:

$$kWh = \frac{1}{11.81} \int_0^t Q_t H_t e \, dt \tag{11-2}$$

where

kW = power available from the project, kW

kWh = energy generated during a time period, kWh

Q = average streamflow during the time period, m^3/sec

H = average head during the time period, m (Head = headwater elevation - tailwater elevation - hydraulic losses)

t = number of hours in the time period

e = overall efficiency expressed as the product of the generator efficiency and the turbine efficiency

In practice, the summation of energy production over the critical period is performed with a sufficiently small time step to provide reasonable estimates of head and, therefore, energy. Two basic approaches are available: flow-duration and sequential analysis.

(2) For run-of-river projects, where the headwater elevation does not vary significantly, the flow-duration approach can be used to estimate average annual energy production. The duration curve can be truncated at the minimum flow rate for power production. The curve can also be truncated for high-flows if the tailwater elevation is too high for generation. The remaining curve is converted to capacity-duration and integrated to obtain average annual energy. Hydropower Analysis Using Flow-Duration Procedures HYDUR (HEC 1982d) was developed to perform energy computations based on flow-duration data. EM 1110-2-1701 describes HYDUR in paragraph C-2*b* and the flow-duration method in Section 5-7.

(3) Sequential streamflow analysis will be applied to most reservoir studies. The procedure allows detailed computations of the major parameters affecting hydropower (e.g., headwater and tailwater elevation, efficiency, and flow release). By performing the analysis in sufficiently small time steps, an accurate simulation of the reservoir operation, power capacity and energy production can be obtained. Chapter 5 of EM 1110-2-1701, Sections 5-8 through 5-10, provides a discussion of sequential routing studies. Appendix C provides information concerning computer programs that are available for use in these studies.

f. Hydropower effect on other project purposes. Usually, power generation must have a high priority relative to other conservation uses. Consequently, thorough investigations of all aspects of the power operation must be conducted to ensure that the power operations do not create intolerable situations for other authorized or approved water uses. Likewise, the power operations must be coordinated with other high priority purposes such as flood control and municipal water supply to ensure that the planned power operation will not interfere with the operations for these purposes. The operation rules that are necessary to effect the coordination are usually developed and tested using engineering judgment and detailed sequential routing studies. However, it is necessary to define the interactions between power and other project purposes before initiating operation studies.

(1) Power generation is generally compatible with most purposes that require releases of water from a reservoir for downstream needs. However, power generation usually competes with purposes that require withdrawal of the water directly from the reservoir or that restrict fluctuations in the reservoir level. Flood-control requirements frequently conflict with power operations because flood-control needs may dictate that storage space in a reservoir be evacuated at a time when it would be beneficial to store water for use in meeting future power demands. Furthermore, when extensive flooding is anticipated downstream from a reservoir project, it may be necessary to curtail power releases to accomplish flood-control objectives. It is often possible to pass part or all of the flood-control releases through the generating units, thereby reducing the number of additional outlets needed and significantly increasing the energy production over what would be possible if the flood-control releases were made through conduits or over the spillway. Also, many of the smaller floods can be completely regulated within the power drawdown storage, an operation that is beneficial to power because it provides water for power generation that might otherwise have been spilled. This joint use can reduce the exclusive flood-control storage requirements and also reduce the frequency of use of flood-control facilities.

(2) Water for municipal, industrial, or agricultural use can be passed through the generating units with no harmful effects if the point of withdrawal for the other use is below the point where the power discharge enters the river. Re-regulation may be required for hydropower peaking operations to “smooth out” the power releases. Conflicts between power and these consumptive uses more likely occur when the withdrawal for other uses is directly from the reservoir. When the withdrawal is from the reservoir of a storage project, the inclusion of power as a project purpose may require that special attention be given to intake facilities for the other purposes because of the relatively large drawdown associated with storage projects.

(3) Low-flow augmentation for navigation, recreation, or fish and wildlife can be accomplished by releases through power generating units. In the case of baseload projects, the power release is ideally suited for this type of use. With peaking projects, however, a re-regulation structure may be necessary to provide the relatively uniform releases that might be required for navigation or for in-stream recreation. Release of water for quality enhancement can sometimes be accomplished through the generating units. Although the intakes for the turbines are usually located at a relatively low elevation in the reservoir where dissolved oxygen content might be low, the oxygenation that occurs in the tailrace and in the stream below the project may produce water with an acceptable dissolved oxygen content. The water released from the lower levels of the reservoir is normally at a relatively low temperature and, thus, ideal for support or enhancement of a cold-water fishery downstream. If warm waters are needed for in-stream recreation, for fishery requirements, or for any other purpose, a special multilevel intake may be required to obtain water of the desired temperature.

(4) Recreation values at a reservoir project may be enhanced, somewhat, by the inclusion of power because a much larger reservoir is frequently required, and that may increase opportunities for extensive recreational activities. Unfortunately, however, the large drawdowns associated with the big storage projects create special problems with respect to the location of permanent recreational facilities and may create mudflats that are undesirable from the standpoint of aesthetics and public health requirements. The drawdown may also expose boaters, swimmers, and other users to hazardous underwater obstacles unless provisions are made to remove these obstacles to a point well below the maximum anticipated drawdown. Obviously the time of occurrence of extreme drawdown

conditions is an important factor in determining the degree of conflict with recreation activities.

11-6. Water Quality Considerations

a. Water quality definition. Water quality deals with the kinds and amounts of matter dissolved and suspended in natural water, the physical characteristics of the water, and the ecological relationships between aquatic organisms and their environment. It is a term used to describe the chemical, physical, and biological characteristics of water in respect to its suitability for a particular purpose. The same water may be of good quality for one purpose or use, and bad for another, depending on its characteristics and the requirements for the particular use.

b. Water quality parameters. In general, physical parameters define the water quality characteristics that affect our senses while chemical and biological parameters index the chemical and biological constituents present in the water resource system. However, these are not independent, but are actually highly related. For example, chemical waste discharges may affect such physical factors as density and color, may alter chemical parameters such an pH and alkalinity, and may affect the biological community in the water. Even so, the physical, chemical, and biological subdivision is a useful way to discuss water quality conditions. The following sections describe the water quality parameters frequently associated with reservoirs. EM 1110-2-1201 provides details on parameters, assessment techniques, plus data collection and analysis.

11-7. Water Quality Requirements

A wide variety of demands are made for the use of water resources. Water of a quality that is unsatisfactory for one use may be perfectly acceptable for another. The level of acceptable quality is often governed by the scarcity of the resource or the availability of water of better quality.

a. Domestic use. The use of water for domestic purposes such as drinking, culinary use, and bathing is generally considered to be the most essential use of our water resources. The regulations for the quality of this water are likewise higher than for most (but not all) other beneficial uses of water. In early times, the quality of the water supply source and the quality at the delivery point were synonymous; but the general degradation of both surface water quality and shallow ground water quality has made it necessary, in most cases, for some degree of water treatment to be used to produce acceptable water for domestic use. In recent decades, there has been a strong trend (which is likely to continue) for the quality of the source waters throughout the world to decline as a result of increased urbanization and industrialization and as a result of changes in agricultural practices. At the same time, populations are coming to expect a higher standard of health and well-being; and as a result, the regulations for acceptable domestic water continue to rise and enlarge the role of water treatment.

b. Drinking water standards. Drinking water standards for the world as a whole have been set by the World Health Organization (WHO). One should keep in mind that these standards do not describe an ideal or necessarily desirable water, but are merely the maximum values of contaminant concentration which may be permitted. It is highly desirable to have water of much better quality. In the United States, the Environmental Protection Agency (EPA) sets regulations that legally apply to public drinking water and water supply systems. The regulations are divided into three categories: bacterial, physical, and chemical characteristics. They are defined in terms of maximum contaminant levels (MCL's). Bacterial quality is defined by establishing the sampling sequence, the method of analysis, and the interpretation of test results for the coliform organisms which serve as presumptive evidence of bacterial contamination from intestinal sources. Analysis is generally made for total coliform, fecal coliform, and streptococci coliform. The limits on biological and physical parameters, and on chemical elements or compounds in water are documented in *Water Supply and Sewerage* (McGhee 1991).

c. Quality of source waters. The drinking water standards are the end product of a production line which begins with the source water as a raw material and proceeds through the various unit processes of water treatment and finally water distribution. The quality of source waters for other uses such as agricultural and industrial water supply, fish and other aquatic life, and recreation are set by state regulations of receiving waters. Other specific uses may include regulations for navigation, wild and scenic rivers, and other state-specific needs. The state regulations are subject to EPA approval. The regulations of a given state may take a variety of forms but are often specified by stream reaches including associated natural or constructed impoundments. Each reach may be classified for its various water uses and water quality standards defined for each use.

(1) Industry uses water as a buoyant transporting medium, cleansing agent, coolant, and as a source of steam for heating and power production. Often the quality required for these purposes is significantly higher than that required for human consumption. The availability of water of high quality is often an important parameter in site

selection by an industry. The needs of a particular industry as to both quantity and quality of water varies with the competition for water, the efficiency of the plant process with regard to water utilization, the recycling of water, the location of the plant site and the ratio of the cost of the water to the cost of the product. For economic reasons and for reasons of quality control and operation responsibility, industries with high water requirements usually develop their own supply and treatment facilities.

(2) Farmstead water is that water used by the human farm population for drinking, food preparation, bathing, and laundry. It also includes water used for the washing and hydrocooling of fruits and vegetables, and water used in the production of milk. The quality of water desired for farmstead use is generally that required for public water supplies. It is not feasible to set rigid quality standards for irrigation waters because of such varied and complex factors as soil porosity, soil chemistry, climatic conditions, the ratio of rainwater to irrigation water, artificial and natural drainage, relative tolerance of different plants, and interferences between and among constituents in the water. Examples of the latter are the antagonist influence of calcium-sodium, boron-nitrates, and selenium-sulfates.

(3) Water quality parameters of importance for irrigation are sodium, alkalinity, acidity, chlorides, bicarbonates, pesticides, temperature, suspended solids, radionuclids, and biodegradable organics. All of these factors need to be weighed carefully in evaluating the suitability of water for irrigating a particular crop. There is surprisingly little data on the effect of water quality on livestock, but generally they thrive best on water meeting human drinking water standards. The intake of highly mineralized water by animals can cause physiological disturbances of varying degrees of severity. In some cases, particular ions such as nitrates, fluorides, selenium salts, and molybdenum may be harmful. Certain algae and protozoa have also been proven toxic to livestock.

(4) The basic purpose of water quality criteria for aquatic life is to restore or maintain environmental conditions that are essential to the survival, growth, reproduction, and general well-being of the important aquatic organisms. These criteria are ordinarily determined without the aid of economic considerations. Generally, a number of major problems arise in establishing water quality criteria for an aquatic community because of the inability to quantify the effects of the pertinent parameters and reduce them to a conceptual model that describes the nature of the biological community which will develop under a given set of conditions. But extensive research should be considered when unusually high concentrations of such parameters as alkalinity, acidity, heavy metals, cyanides, oil, solids, turbidity, or insecticides are known to exist.

(5) For an aquatic system to be acceptable for swimming and bathing, it must be aesthetically enjoyable (i.e., free from obnoxious floating or suspended substances, objectionable color and foul odors), it must contain no substances that are toxic upon ingestion or irritating to the skin or sense organs, and it must be reasonably free of pathogenic bacteria. Standards generally do not cover the first two terms as related to swimming and bathing except in qualitative terms. In the United States, numerous standards exist for bacteriological quality based on the coliform count in the water. Generally, the standards range downward from 1,000 coliform bacteria per 100 ml to as low as 50 per 100 ml. Such standards are not based on demonstrated transmittal of disease, but have been established because in these ranges the standards are economically reasonable and no problems appear. The use of an aquatic system for boating and aesthetic enjoyment is generally not so demanding as the requirements for swimming or the propagation of fish and aquatic life although these three water uses are usually closely linked.

11-8. Reservoir Water Quality Management

Reservoirs may serve several purposes in the management of water quality. If used properly, substantial benefits can be achieved. On the other hand, unwise use of reservoirs may cause increased quality degradation. Benefits may accrue as a result of detention mixing or selective withdrawal of water in a reservoir or the blending of waters from several reservoirs. The effects of improper management are often far-reaching and long-term. They may range from minor to catastrophic, and may be as obvious as a fish kill or subtle and unnoticed. It is essential that all water control management activity and especially real-time actions include valid water quality evaluation as a part of the daily water control decision process. It must be understood that water quality benefits accumulate slowly, build on each other, and can become quite substantial over time. This is in contrast to the sudden benefits that come from a successful flood-control operation. Water quality management requirements, objectives, and standards are presented in EM 1110-2-3600.

a. Reservoirs in streams. The presence of a reservoir in a stream affects the quality of the outflow as compared to the inflow by virtue of the storage and mixing which takes place in the reservoir. The effect of such an impoundment may be easily evaluated for conservative parameters if the waters of the reservoir are sufficiently mixed that an assumption of complete mixing within an analysis time period does not lead to appreciable error. However, this assumption is limited to relatively small, shallow reservoirs.

b. Reservoir outflow and inflow. The simplest technique requires the assumption that the reservoir outflow during a given time period is of constant quality and equal to the quality of the reservoir storage at the end of the computation time period. It is then assumed that the inflow for the time period occurs independently of the outflow, and reservoir quality is determined by a quality mass balance at the end of the time period. This approach is equivalent to the mass balance of water in reservoir routing.

c. Reservoir water quality. Simple mass balance procedures may be applicable is some situations; however, usually more comprehensive methods should be considered. Chapter 4, "Water Quality Assessment Techniques," in EM 1110-2-1201 describes various techniques available for assessing reservoir water quality conditions. There is a hierarchy of available techniques that reflects increasing requirements of time, cost, and technical expertise. The increasing efforts should provide accompanying increases in the degree of understanding and resolution of the problem and causes. This hierarchy includes screening diagnostic and predictive techniques, which are described.

d. Reservoirs as detention basins. Reservoir mixing is a continual process where low inflows of poor quality are stored and mixed with higher inflows of better quality. Generally, this is accomplished in large reservoirs where annual or even multiple-year flows are retained, but the concept extends to small reservoirs in which weekly or even daily quality changes occur due to variability of loading associated with the inflow.

(1) The use of a reservoir as a mixing devise should be considered whenever the inorganic water quality is unacceptable during some periods but where the average quality falls within the acceptance level. Lake Texoma on the Red River is an example of a reservoir which modifies the quality pattern. Although monthly inflow quality has equalled 1,950 mg/l chloride concentration, the outflow has not exceeded 520 mg/l.

(2) Many materials which enter a reservoir are removed by settling. This applies not only to incoming settleable solids, but also to colloidal and dissolved materials which become of settleable size by chemical precipitation or by synthesis into biological organisms. Reservoirs are often used to prevent such settleable material from entering navigable rivers where settleable materials would interfere with desired uses. However, reservoirs that receive substantial sediment will have a short useful life. Planning should include evaluation of the ultimate fate and possible replacement of such reservoirs. Reservoir sedimentation is covered in EM 1110-2-4000.

e. Reservoirs as stratified systems. Reservoirs become stratified if density variations caused by temperature or dissolved solids are sufficiently pronounced to prevent complete mixing. This stratification may be helpful or harmful depending on the outlet works, inflow water quality, and the operating procedure of the reservoir.

(1) Temperature stratification can be beneficial for cold-water fisheries if the water which enters the reservoir during the cooler months can also be stored and released during the warmer months. The cooler water released during the warm months can also be valuable as a cooling water source, can provide for higher oxygen transfer (re-aeration) or slower organic waste oxidation (deoxygenation), and can make the water more aesthetically acceptable for water supply and recreational purposes.

(2) Dissolved oxygen stratification usually occurs in density stratified lakes, particularly during the warmer months. The phenomenon occurs because oxygen which has been introduced into the epilimnion by surface re-aeration does not transfer through the metalimnion into the hypolimnion at a rate high enough to satisfy the oxygen demand by dissolved and suspended materials and by the benthal organisms. Thus, the cool bottom waters which are sometimes desirable may be undesirable from a dissolved oxygen standpoint unless energy dissipation structures are constructed to transfer substantial oxygen into the reservoir pool or the reservoir discharge. Mechanical reservoir mixing to equalize temperature and transfer oxygen to lower reservoir levels is one possible tool for managing reservoir water quality.

f. Reservoirs as flow management devices. Reservoirs may improve water quality by merely permitting the management of flow. This management may include maintenance of minimum flows, blending selective releases from one or more reservoirs to maintain a given stream quality, and the exclusion of a flow from a system by diversion.

(1) Minimum flow is often maintained in a stream for navigation, recreation, fish and wildlife, and water rights purposes. Such flows may also aid in maintaining acceptable water quality.

(2) There is general agreement that water may be stored and selectively released to help reduce natural water quality problems where source control is not possible, and

also that water should not be stored and released solely to improve water quality where similar improvement may be achieved by treatment at the source. The use of a water resource to dilute treatable waste materials is regarded as the misuse of a valuable resource in most cases.

(3) Selective release of water from one or more reservoirs may help improve quality at one or more downstream locations. Such releases may be one of the governing factors in establishing reservoir management rules. The water to be released may either be good quality water that will improve the river quality or poor quality water that is to be discharged when it will do a minimum of harm (e.g., during high flow). The water quality version of the HEC-5 reservoir simulation program (HEC-5Q) is designed to perform quality analysis based on a reservoir simulation for quantity demands and subsequently determine additional releases to meet quality objectives (HEC 1986). Section III, Chapter 4 of EM 1110-2-1201 describes various predictive techniques, including numerical and physical models.